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(54) **Determing position and time of scintillation event**

(57) A system for encoding the 2-dimensional position of a scintillation event on the output phosphor screen of a photoelectronic photon-counting image intensifier 6 also records the time of occurrence of the scintillation event with very high temporal resolution (better than 25 microseconds) by the novel application of photodiode array devices known as "microstrip" arrays for optical detection. The horizontal and vertical locations of scintillation events are separately encoded by imaging the phosphor screen simultaneously onto two such microstrip arrays 20 and 21 which are oriented perpendicularly to one another eg by means of a beam splitter 17. Another splitter 19 may direct 1% of the beam to a detector 18 for triggering the read-out cycle of amplifier arrays 22 and 23 connected to the microstrip arrays.

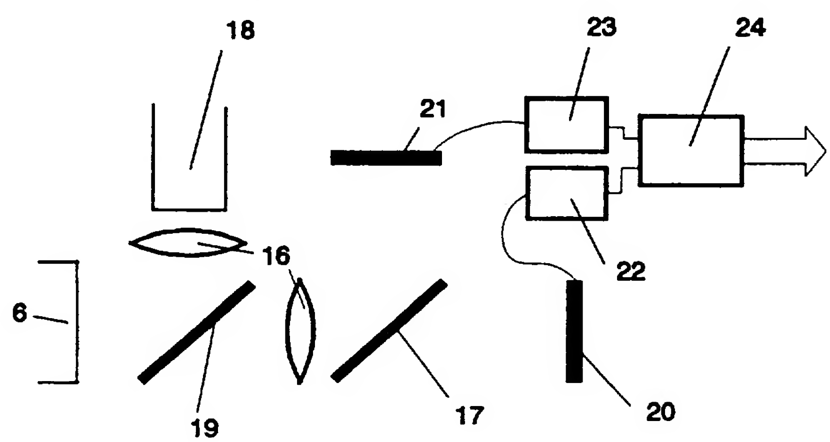

Figure 4

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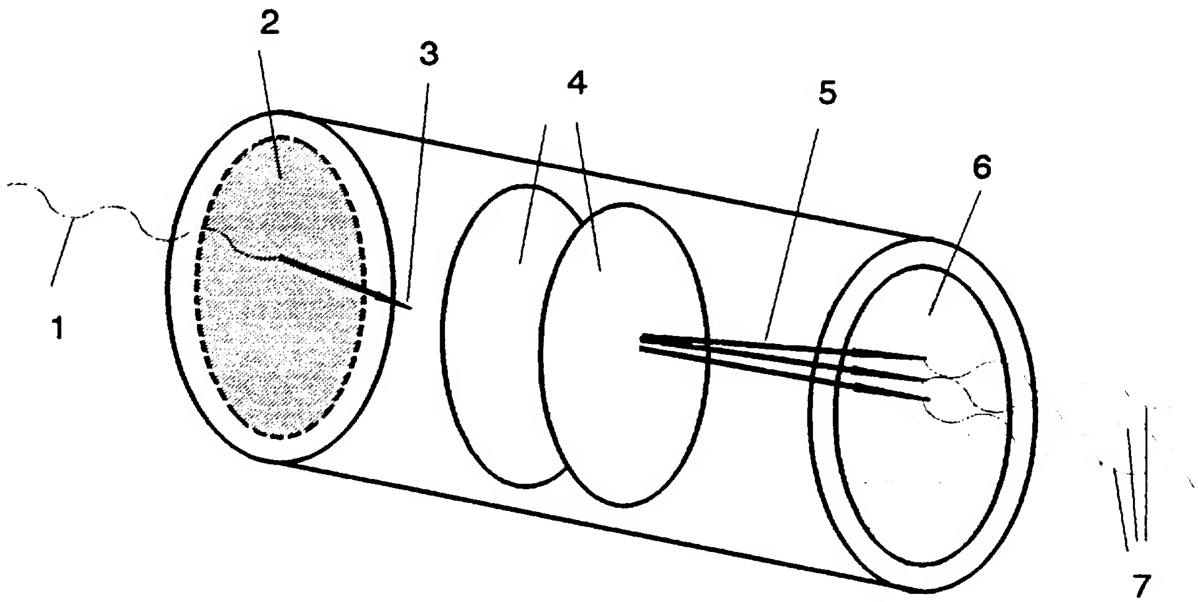

Figure 1

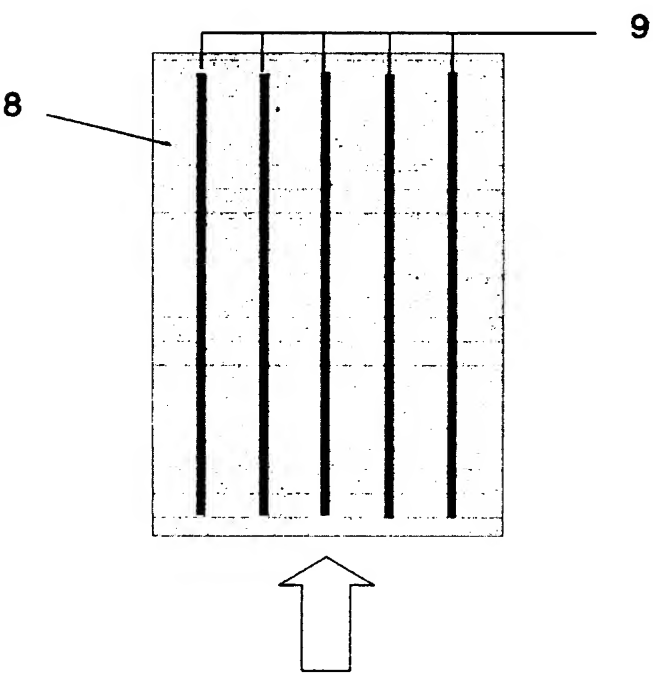

Figure 2

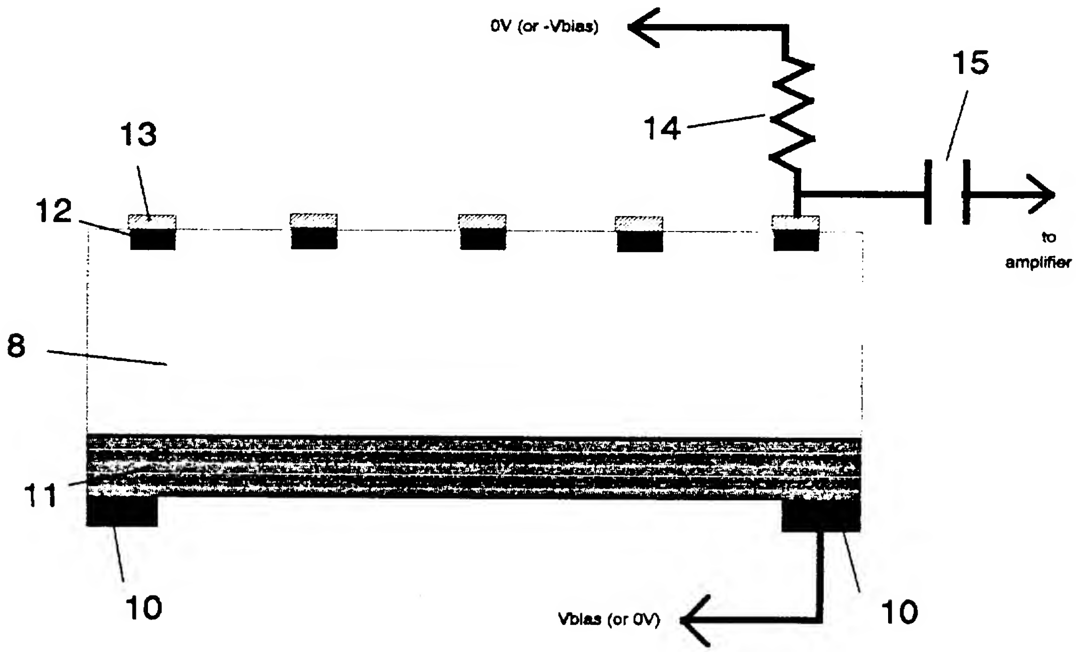

Figure 3

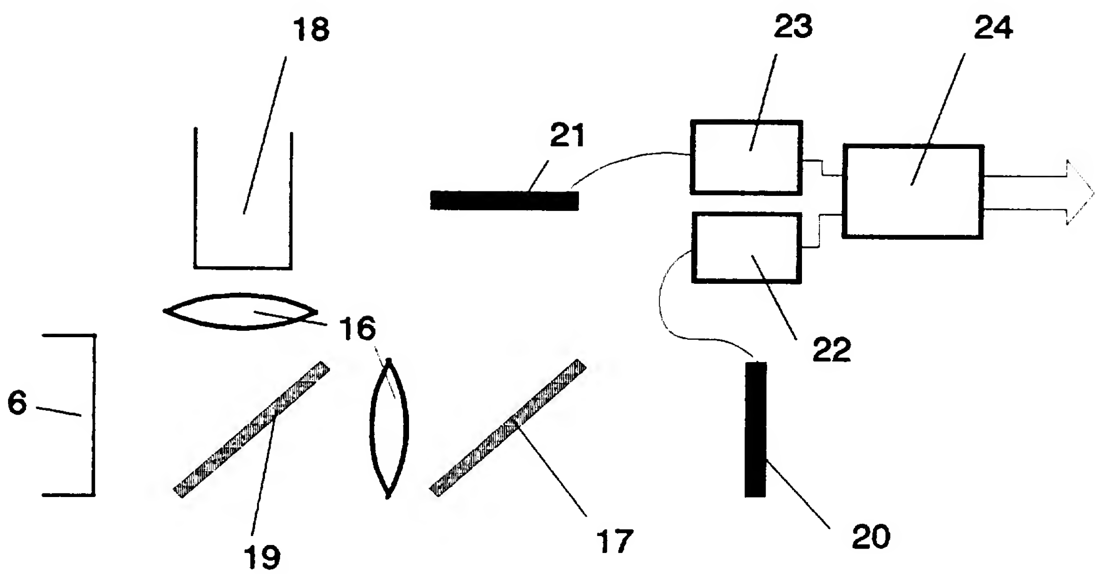

Figure 4

A system for encoding the 2 dimensional position of a scintillation event on the output phosphor of a photoelectronic image intensifier allowing high precision in the determination of the time of occurrence of that scintillation.

This invention generally relates to a method whereby the 2-dimensional spatial location of a scintillation event occurring on the output phosphor screen of a photon-counting image intensifier can be determined and simultaneously the time of occurrence of that scintillation event can be determined with high precision (better than 25 microseconds).

Photoelectronic image intensifiers capable of unambiguously detecting the arrival of individual photons (or ionising particles) find wide application in analytical science. Examples include astronomical imaging and spectroscopy of faint objects, medical imaging using ionising radiation or via optical/near-infrared diaphanography, X-ray diffractometry of crystals or biomolecules and the reconstruction, via higher order correlation analysis, of images of objects viewed through turbulent media. The principle of operation of such an image intensifier is that it is arranged that the incident signal (photon or ionising particle), upon interaction with said device, should eject one or more electrons, either by the photoelectric effect within a specially designed photocathode or by direct ionisation of materials within the device. This electron signal is then amplified by a suitable cascade process brought about by the application of a suitable voltage, thus creating a suitably intense accelerating electric field, together with the presence, within said device, of suitable secondary emitting structures. These structures are fabricated such that a single incoming electron is capable of ejecting several electrons, which themselves further contribute to the cascade process, eventually forming an output electron "shower" of many thousands or millions of electrons. The construction of the device is such as to ensure that the spatial location of this final electron shower is uniquely related to the spatial arrival location of the detected photon/particle. This output electron signal can then be directly detected by charge sensitive electronic circuitry or, of direct relevance to this invention, the electron shower can be arranged to impinge upon a suitable screen which will fluoresce in response to bombardment by the electron shower. The end result is that each detected photon/ionising particle will result in a scintillation of light on this fluorescent screen, the position of which is correlated with the position of arrival of the photon/ionising particle and the time of occurrence of which corresponds to the time at which the photon/ionising particle first interacted with the detection device (plus a small propagation delay). Figure 1 represents, in schematic fashion, such a device and the form of the output signal.

Numerous methods have been proposed whereby the position and time-of-occurrence of this scintillation can be encoded into an electronic format. Such systems have included recording on photographic film followed by electronic scanning using microdensitometry, direct detection using television camera tubes of enhanced sensitivity (eg

Silicon Intensified Target (SIT) camera tubes) or solid-state television cameras using charge-coupled devices (CCD's), detection via solid-state light sensors or detection via positional encoding systems using arrays of optical masks and photomultiplier tubes.

The present invention relates to a new method, distinct from those described above, whereby the spatial location of a scintillation event can be determined and converted into electronic format and the time of occurrence of the event similarly determined with high precision.

The essence of the invention is to detect the two components of the scintillation event position by imaging the light from this event onto two distinct arrays of photodiodes. Such arrays are in common use as charged particle detectors within the high energy particle physics community, where they are commonly referred to as "Silicon Microstrips", silicon being the most common, but not the exclusive, semiconductor of embodiment. These arrays comprise a large number of distinct photodiodes, each having a very high (>10) aspect ratio, arranged to run parallel to each other so as to appear as a large number of parallel "strips" (Figure 2). The anodes (and possibly also the cathodes) of these diodes are electrically separated from each other such that the signal from each diode can then be separately measured. A suitable bias voltage is applied to each diode to reverse bias the diode junction, thus creating a depletion layer within the bulk semiconductor. When a suitable "signal" impinges on such a diode array, be it a particle or particles or an electromagnetic photon or photons, electron-hole pairs are created within the depletion region and drift, under the influence of the applied electric field, to the anodes and cathodes of the array. The impinging signal thus manifests itself as a small electrical current which can be detected using suitable charge-sensitive or current-sensitive amplifiers. Since the diodes in the array are discrete, the linear position of interaction of the impinging signal can be readily determined by noting from which diode the resultant current emanates (Figure 3).

The present invention relates to the novel application of these devices to the encoding of the 2 dimensional location and time of occurrence of a scintillation event from a photoelectronic image intensifier of high amplification (commonly referred to as a "high gain" or "photon-counting" image intensifier). Since the diode arrays described above are sensitive to optical,ultra-violet and near-infrared photons, such an array can be used to determine one component of the spatial position of the scintillation by imaging the fluorescent screen onto the array. Similarly the time of occurrence of the event can be determined by recording the time of occurrence of the output electrical current from the diode array. In this regard it is important to note that a crucial feature of the invention is that this time of occurrence can be recorded with very high precision both because the diodes and associated amplifiers have very fast (typically less than 1 microsecond) response times and because each diode is provided with a separate amplifier (the combination of a diode and its amplifier hereafter being referred to as a "channel"), such that the detection of a signal by the array can, in principle, be registered in a time determined by the response time of a single channel. In this regard the invention differs from all other

methods of employing a solid-state array sensor to encode the position of such scintillation events, where the temporal precision is limited by the time required to access the complete array.

It will be apparent that if the fluorescent screen is imaged onto two such arrays, using suitable beam-splitting optics, and the directions of orientation of the diodes in these two arrays are non-parallel, then the 2 dimensional location of the scintillation and its time of occurrence can be encoded as claimed. In the preferred embodiment, the diode arrays, when overlapped, would form a cartesian grid. Non-cartesian strip geometries could also be employed using suitable position encoding electronics

The present invention is a means of encoding the spatial and temporal output signal from a high gain photoelectronic image intensifier when that output signal is an optical signal comprising discrete scintillations of light formed upon the fluorescent output screen of said intensifier. A specific embodiment of this invention will now be described by way of example with reference to the accompanying drawings in which:-

Figure 1 shows, in schematic form, the construction of a photoelectronic image intensifier and the form of the output signal as a scintillation of light on the output fluorescent screen of the device.

Figure 2 shows, in schematic form, a microstrip detector array, showing the orientation and (representative) aspect ratio of the individual diodes.

Figure 3 shows, in schematic form, a cross-sectional view of a microstrip array, showing the method of biasing the array and of sensing the signal current (for clarity the connections to only one of the anode strips is shown).

Figure 4 shows, in schematic form, the optical layout for the preferred embodiment of the proposed image intensifier read-out system.

The first component that is required is an image intensifier (figure 1) of adequate amplification. When an optical photon 1 is incident upon the photocathode 2 causing the ejection from the photocathode of a primary electron 3, this electron must be adequately amplified by the electron gain stages 4 such that the electron shower 5, when incident upon the phosphor screen 6 produces output scintillations 7 bright enough to produce, after consideration of all optical transmission losses and inefficiencies, sufficient charge within a diode to be measured by the diode read-out electronics. The amplification required of the intensifier is thus a function of:-
a) the optical coupling inefficiencies between the intensifier phosphor screen and the diode arrays
b) the emission spectrum of the phosphor screen
c) the sensitivity of the semiconductor material to light of specific wavelengths
d) the refractive index mismatch between the semiconductor material and

the ambient medium within the instrument

e) The magnitude of the current flowing through the reverse biased diodes (commonly and hereafter referred to as the "leakage current")

f) the capacitance of the microstrip diodes and the capacitance of the connecting wires between the diodes and amplifiers

g) the voltage and current noise densities of the amplifiers

h) the size of the image of the scintillation formed on the diode array insofar as this causes the signal per diode to be decreased.

In addition to possessing sufficient amplification to produce a measurable signal within the diode array, the intensifier must also be so constructed as to produce scintillation events whose temporal duration is substantially shorter than the temporal precision required of the read-out system. This feature, necessary to avoid problems of multiple recording of the same scintillation event, requires that the intensifier use a so-called "fast phosphor", meaning that the phosphor be of a type which produces a rapidly decaying scintillation after stimulation by the incident electron shower. In the design presented here, it is envisaged that this decay time should be substantially shorter than 25 microseconds.

The next major components of the proposed system are the diode arrays (hereafter referred to as the "microstrips") which are depicted in figures 2 and 3 (figure 3 represents a cross-sectional view of the array depicted in figure 2, viewed in the direction denoted by the broad arrow at the base of figure 2). In the envisaged embodiment of the design, these will be fabricated using silicon as the bulk semiconductor 8, but the design is not tied to any specific semiconductor, provided that the semiconductor possesses reasonable sensitivity to the radiation emitted by the intensifier phosphor screen. The microstrip arrays, which are commercially available, will be fabricated in the standard manner although certain detailed specifications may be requested of the manufacturer to optimise their performance, namely:-

a) if the image of the phosphor screen is to be formed on the face of the microstrip array containing the discrete anodes (or cathodes) 9 (hereafter referred to as the "front side"), the means of making the electrical connection to the anodes may be optimised by:

i) specifying the width of the contact metal strip 13 to be as narrow as possible, to minimize the area of the array which is insensitive to light.

ii) specifying that the contact metal strip 13 be removed from the majority of the surface area of the anode semiconductor implant 12, contact then being made only at restricted points.

iii) specifying that the electrical contact 13 be fabricated using a transparent conductive material such as tin-oxide, rather than metal.

b) if the image of the phosphor screen is to be formed on the face of the array comprising the common cathode (or anode) 11 (hereafter referred to as the "backside"), the metal electrical contact 10 will be removed from the majority of the array area, contact being restricted to a thin peripheral strip or other sparse geometry.

c) to optimise the sensitivity of the array, it may be requested that the manufacturer deposit a thin coating of fluorescent material designed to

absorb incident light from the scintillation event and re-emit light of a different wavelength, this re-emission wavelength being such that the semiconductor material of the microstrip array is more sensitive to this light than that originally emitted by the intensifier phosphor. This technique is common in the related field of CCD manufacture.

A further refinement that may be applied is the application, within this invention, of microstrips in which both the anodes and the cathodes are discrete. These devices, commonly referred to (and referred to hereafter) as "double-sided microstrips", allow both components of the spatial location of the detected signal to be recorded by a single array. This is achieved by arranging that the direction of orientation of the anode and cathode strips are non-parallel, in which case one component of the spatial position is recorded by sensing current comprising electrons collected at one face of the array, and the other component is recorded by sensing holes collected at the opposite face. Such double sided arrays can be employed either to obviate the need for two arrays and the dual-imaging optics alluded to in the previous section, or by incorporating them directly into the preferred embodiment described here, in which case they can be used to introduce a two-fold redundancy into the encoding process, such that if any diode should fail to function, there remains the possibility to detect an imaged scintillation occurring at the position of the malfunctioning diode using the corresponding diode in the other array. The problem of malfunctioning diodes, which would otherwise lead to a line region within the imaged area of the phosphor screen within which no scintillation events could be detected, is then avoided unless, by misfortune, both diodes corresponding to a given spatial location should fail to function. Clearly this scheme of introducing redundancy to avoid problems of malfunctioning diodes could be extended to include more than two arrays, by the provision of more elaborate coupling optics, capable of producing more than two images of the phosphor screen.

The next major component of the invention is the encoding electronics used to convert the output electrical current from the microstrip diodes into a spatial position and time of occurrence. As with the microstrip arrays themselves, the preferred embodiment utilises, as far as possible, available components previously developed for the purpose of high energy particle detection but the use of specifically designed and constructed circuitry is not excluded. As previously stated, the high temporal resolution of the proposed read-out system is achieved through the ability, in principle, to detect the signal in a diode independently of the other diodes, to which end it is a necessary feature of the proposed design that each diode be provided with its own amplifier, the purpose of which is to convert the small current generated by the diode into a current or voltage of sufficient amplitude as to be unambiguously detected and then processed by subsequent electronics. Due to the large number of separate diodes and the need to restrict the physical size of the read-out system, the preferred embodiment utilises arrays of charge sensitive amplifiers fabricated onto a single semiconductor substrate. Such arrays, which are also commonly available, typically contain over one hundred individual amplifiers, each of which is separately connected to a single microstrip diode by an ultrasonically welded wire bond. In the

preferred embodiment, one or a small number of such devices (hereafter referred to as "amplifier arrays") would be attached to each microstrip array for the purpose of converting electrical current generated within a microstrip diode into a measurable voltage or current. In the preferred embodiment the connection between a diode and its amplifier would not be direct but via a suitable capacitance 15 (commonly and hereafter referred to as "ac coupling" or "capacitative coupling". Such a connection is required to ensure that the leakage current flowing through the reverse biased diode via the diode bias resistor 14 does not reach the amplifier, with the exception of the random component (commonly and hereafter referred to as the "shot noise component") of this current which then contributes to the overall noise associated with the measurement of the detected charge. In the preferred embodiment, the amplifiers would be of a type commonly referred to as "charge sensitive", in which the current is detected by integration upon a small feedback capacitor within the amplifier, thus producing an output voltage proportional to the integral of the diode current with respect to time. Since the preferred embodiment utilises currently available components, the charge sensitive amplifiers would be of a type commonly known as the "switched capacitor" type. In this type of amplifier, signal current is integrated on this feedback capacitor continuously, until it is desired to read out the signal, after which the signal charge is erased, generally by applying an electrical short-circuit across the feedback capacitor. An additional feature of such amplifiers is generally to implement the noise-reduction method commonly known as "correlated double sampling", in which the final output signal is taken as the difference between the amplifier output after resetting but before the detection of an event and after detection of the event. This differencing scheme is intended to remove any signal due to charge left on the feedback capacitor by Johnson noise within the field effect transistor (FET) used to short-circuit the feedback capacitor. Since the amplifier array cannot, by itself, determine whether a signal has been detected by a diode, efficient operation of such a device requires that a separate signal (hereafter referred to as the "trigger signal") be provided to the amplifiers which indicates that the array amplifier signals should be read out and the amplifiers reset, in the manner described. Numerous amplifier arrays are available commercially, including those which then output the individual amplifier voltages in a serial fashion. Such serial output causes the process of event position encoding to become relatively slow however, being equal to the total time required to electronically address each diode in the microstrip in turn. Typical operating values of 128 diodes per microstrip array and a serial output rate from the amplifier array of 5 million samples per second leads to an event position encoding time of approximately 25 microseconds. Since only one scintillation event can be unambiguously encoded in this period, this leads to the comparatively poor figure of 40,000 events per second as the maximum rate at which events can be detected using such a read-out system. The preferred embodiment would thus utilise switched capacitor amplifier arrays possessing a so-called "sparse read-out" capability, in which each amplifier output is equipped with a comparator which determines whether that amplifier output exceeds some

pre-defined threshold. The process of reading out the amplifier array then consists of determining those amplifiers in the array which have detected a signal exceeding this threshold (hereafter referred to as a "valid signal") and subsequently determining the amplitude of the output signals of those amplifiers only. Since the first stage of this process requires one simply to determine the status of a binary status flag for each amplifier, it is much faster than the process of determining the analogue output signal of each and every amplifier. A typical rate for this process being 20MHz, the time required to determine those amplifiers which contain a valid signal is only 6 microseconds. Since, for typical scintillation events only a few (typically 5 or fewer) amplifiers will contain a valid signal, and since the processes of interrogating the analogue output of an amplifier and searching for the next amplifier containing a valid signal can occur in parallel, this figure will also represent, in general, the time required to determine the analogue output signals of all amplifiers containing a valid signal. Once this analogue data has been acquired, numerous schemes can be employed to determine the position of the scintillation event on the microstrip array. The simplest scheme, yielding a spatial resolution determined solely by the separation between the diodes is to ascribe the position of the scintillation to the diode containing the largest signal. An obvious refinement, capable of yielding spatial resolutions in excess of the spatial separation between diodes, is to employ the technique commonly known as "charge division", in which the signal in two or more neighbouring diodes is compared (generally but not exclusively by simple ratioing) in order to determine the event position to an accuracy equal to some fraction of the diode separation. The spatial resolution of this method is determined by the diode separation and by the signal-to-noise ratio (SNR) of the valid signals.

Although the preferred embodiment employs amplifier arrays of the "switched capacitor" type, the general concept of the proposed image intensifier read-out system is applicable to other types of amplifier array, in particular arrays of amplifiers in which the feedback capacitor is electronically shunted by a resistance such that their analogue output in response to a signal being detected by a diode has the form of a shaped voltage or current pulse of duration typically a few microseconds. Such amplifiers are commonly referred to as "self-triggering" in that they are capable of themselves providing a trigger signal indicating that a signal has been detected by the microstrip array.

It will be evident that, in addition to the event location, the time-of-occurrence of the event can be readily determined by means of a high speed digital clock.

The next component of the proposed read-out system is the optical coupling and (in the preferred embodiment) triggering system. The purpose of the optical coupling system is to relay two images of the phosphor screen, with good optical coupling efficiency, onto the microstrip arrays. The purpose of the triggering system is to provide a trigger signal to the switched capacitor amplifier arrays to cease integrating the signal and to commence the read-out cycle. During the read-out cycle it is important that the components of the amplifier onto which the integrated charge from the feedback capacitor is transferred

(commonly and hereafter referred to as "charge storage capacitors") remain electrically isolated from the feedback capacitor and the diodes, to prevent ambiguities should another scintillation occur during the event encoding process.

Figure 4 shows, in schematic form, the layout of the preferred embodiment. Here, the image of the phosphor screen is relayed to the microstrips by means of coupling lenses 16 of low focal ratio (f1.4 or lower) and a beamsplitter 17 (prismatic, pellicle or a half-silvered mirror). In other embodiments, a fibre-optic beam-splitter could be employed which may lead to higher optical coupling efficiency.

In the preferred embodiment, a trigger signal is obtained by diverting a small (typically 1%) fraction of the light emanating from the phosphor screen into a high sensitivity photomultiplier tube 18 via a glass plate 19. The output from this photomultiplier tube, after suitable thresholding, can then be used to detect the occurrence of a scintillation event and trigger the read-out cycle of the amplifier arrays 22 & 23 connected to the x and y microstrip arrays 20 & 21. In other embodiments the trigger could be derived using an avalanche photodiode or non-optically by sensing current pulses within the electrical connection to the phosphor itself.

In all cases the outputs from the amplifiers are fed into encoding electronics 24 to produce the final output data in the form of the x and y positions and time of occurrence of the scintillation.

CLAIMS.

1) A method and apparatus whereby the two dimensional position and time of occurrence of output optical scintillation events from a suitably constructed image intensifier can be encoded with high precision by imaging the phosphor screen onto two or more arrays of light sensitive photodiodes, of a type commonly referred to as "microstrips" fabricated from a suitable semiconductor material and connected to a suitable array of charge sensitive amplifiers.

2) A method and apparatus as in claim 1) which is made more immune to the deleterious effects of malfunctioning diodes, faulty connections between diodes and amplifiers or faulty amplifiers by using:-

   a) 4 or more single-sided microstrips with the intention of introducing redundancy into the encoding scheme such that a scintillation event occurring at the position of a defective diode will nevertheless be detected by the corresponding diodes in the other arrays.

   b) 2 or more double sided microstrips with the same intention as above.

3) A method and apparatus as claimed in any preceding claim in which the trigger pulse required by certain types of amplifier arrays is provided optically via a photomultiplier tube or avalanche or conventional photodiode or electrically by sensing current pulses within the phosphor electrode.

4) A method and apparatus as claimed in any preceding claim in which the location of the image tube scintillation may be determined to an accuracy given by the separation between diodes by locating the peak signal within the array.

5) A method and apparatus as claimed in any preceding claim whereby the location of an image tube scintillation may be determined to an accuracy exceeding that of the diode separation by comparing the signals in 2 or more neighbouring diodes.

6) A method and apparatus substantially as described herein with reference to figures 1-4 of the accompanying drawings.

Patents Act 1977
Examiner's report to the Comptroller under Section 17
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Search Examiner
R S CLARK

Date of completion of Search
12 APRIL 1995

Databases (see below)
(i) UK Patent Office collections of GB, EP, WO and US patent specifications.

(ii) ONLINE: WPI

Documents considered relevant following a search in respect of Claims :-
1

Categories of documents

X: Document indicating lack of novelty or of inventive step.

Y: Document indicating lack of inventive step if combined with one or more other documents of the same category.

A: Document indicating technological background and/or state of the art.

P: Document published on or after the declared priority date but before the filing date of the present application.

E: Patent document published on or after, but with priority date earlier than, the filing date of the present application.

&: Member of the same patent family; corresponding document.

Category	Identity of document and relevant passages	Relevant to claim(s)
X	GB 2265753 A (ENERGIE ATOMIQUE) page 4 lines 1 to 18	1

Databases: The UK Patent Office database comprises classified collections of GB, EP, WO and US patent specifications as outlined periodically in the Official Journal (Patents). The on-line databases considered for search are also listed periodically in the Official Journal (Patents).

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ABSTRACT:

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